Performance test of wavelength-shifting acrylic plastic Cherenkov detector.

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Abstract

The collection efficiency for Cherenkov light incident on a wavelength shifting plate (WLS) has been determined during a beam test at the Proton Synchrotron facility located in the National Laboratory for High Energy Physics (KEK), Tsukuba, Japan. The experiment was conducted in order to determine the detector's response to photoelectrons converted from photons produced by a fused silica radiator; this allows for an approximation of the detector's quality. The yield of the photoelectrons was measured as a function of the momentum of the incident hadron beam. The yield is proportional to $\sin^2\theta_c$, where θ_c is the opening angle of the Cherenkov light created. Based on estimations and results from similarly conducted tests, where the collection efficiency was roughly 39%, the experimental result was expected to be around 40% for internally produced light from the WLS. The results of the experiment determined the photon collection response efficiency of the WLS to be roughly 62% for photons created in a fused silica radiator and 41% for light created in the wavelength shifter plastic.

Keywords: Cherenkov, Fused Silica, Wavelength shifter

1. Introduction

The use of Cherenkov detectors is now commonplace in the field of nuclear and particle physics. They have been implemented mainly for their particle identification abilities. The number of photons produced per unit energy and path length, for a particle z, is[1][2][3]

$$\frac{d^2N}{dEdx} = \frac{2\pi\alpha z^2}{hc}\sin^2\theta_c \qquad (1)$$

in terms of wavelength it may be written as:

$$\frac{d^2N}{d\lambda dx} = \frac{2\pi\alpha^2 z^2}{\lambda^2}\sin^2\theta_c \qquad (2)$$

Cherenkov detectors are known for requiring a high efficiency in detection and acquisition of photons in the ultra-violet range of the electromagnetic spectrum.

The distribution of the Cherenkov radiation follows $dN/d\lambda \propto 1/\lambda^2$ as implied in equation 2 [3].The number of photoelectrons, produced in a Cherenkov radiator per unit of length L, that will be detected by a PMT is given by:

$$dN_{p.e.} = 370 eV^{-1}cm^{-1}L\int \epsilon_{coll}(E)sin^2\theta_c(E)\mathrm{d}E \quad (3)$$

where, both $\epsilon(E)$, the efficiency for collecting Cherenkov light and converting it into photoelectrons, and $\sin^2\theta_c(E)$ are functions of energy, and L is the thickness of the radiator. [2]. If the previous equation is intergrated over all photon energy ranges such that:

$$N_o = 370 eV^{-1}cm^{-1}\int \epsilon_{coll}(E)\mathrm{d}E \qquad (4)$$

an approximation of the total number of photoelectrons detected can be written as:

$$N_{p.e.} \cong LN_0\langle\sin^2\theta_c\rangle \qquad (5)$$

where, $\langle\sin^2\theta_c\rangle$ is the average squared opening Cherenkov angle, for the photon energy range, and N_o is the Cherenkov detector's quality N_o, also referred to as it's *figure of merit*.Therefore, the collection efficiency

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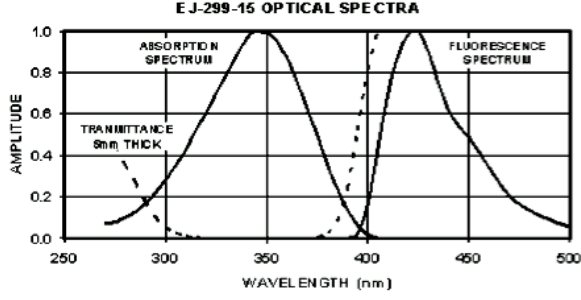
Figure 1: Wavelength shifting plastic's absorption and flouresence spectrum.[9]

Figure 2: Transmittance spectrum of UV grade fused silica.[7]

Table 1: Fused Silica Refractive Index. [8]

Wavelength(nm)	Index of refraction(n)
296.7	1.48873
302.2	1.48719
330.3	1.48054
340.4	1.47858
351.1	1.47671
361.1	1.47513
365.0	1.47454
404.7	1.46962
435.8	1.46669
441.6	1.46622
457.9	1.46498
476.5	1.46372
486.1	1.46313
496.5	1.46252
514.5	1.46156
532.0	1.46071
546.1	1.46008

of the produced Cherenkov radiation is dependent on the sensitivity of the detector to light in the UV range. Most commonly produced detectors using photomultipliers are known to have collection efficiencies of approximately $20 - 25\%$ at 400-420 nm wavelength.The use of a wavelength shifter can increase the collection efficiency of these UV photons to approximately 41% [4].The principle lies in using the wavelength shifter, a substance that converts the wavelength of photons from a shorter to a longer wavelength. The additive has a high absorption ability around 350 nm, as shown in Figure 1. It will then re-emit at a longer wavelength, hence achieving a match between the wavelength shifter peak emission with that of the photomultiplier (PMT). However, an over abundance in the addition of the wavelength shifter can result in a loss of the signal light as a result of attenuation.

1.1. Motivation

The goal of the experiment is to determine the photon detection capability (N_o) of a detector that uses a WLS additive. A previous study was conducted using aerogel as a radiator and WLS as a collector. The collection efficiency of Cherenkov light created within the aerogel yielded poor results due to scattering within the aerogel [4]. This work is a continuation into the usage of a wavelength-shifting plastic as collector of Cherenkov light. There have been advances in other detectors that are composed of aerogel, and wavelength shifter such as the one developed by Novosibirsk [5]. Extensive investigation has been performed upon different types of fused silica as Cherenkov radiators in order to determine their optical properties and radiation hardness [6]. As such, an evaluation of WLS collection capability was performed with a synthetic fused silica as more defined radiator [7]. The results of this experiment will clarify some unanswered questions and will be used to improve upon or decide whether a proposed one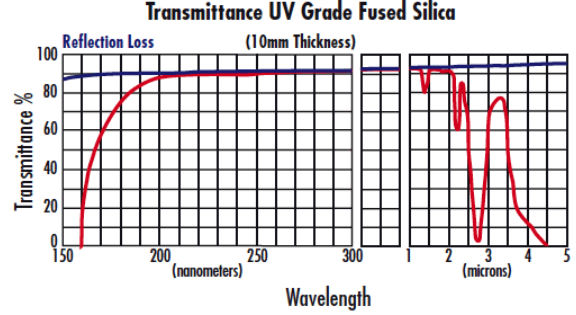-dimensional RICH detector, that uses wave-length shifter bars, would be more efficient and can be used to replace a conventional RICH detector.

2. Experimental Setup

2.1. Detector Description

A test experiment was designed to gauge a detector that incorporates a WLS plastic. The detector consisted of a synthetically made fused silica radiator that was placed 15.0 cm from the wavelength shifter. The radiator has an index of refraction (n_r) of 1.476 correspondences to a wavelength of $\lambda = 351$ nm, and physical dimensions of 50 x 50 x 8 mm^3. A complete listing of the fused siclia's index of refraction as a function of wavelength is presented in Table 1. The acrylic plastic was 1.27 x 10 x 30.5 cm^3 in size. The acrylic bar contained a wavelength shifting flourescent additive [9]. Figure 1 displays the absorption and flourescence spectrum of the wavelength shifter. The transmittance of the radiator is shown in Figure 2. The light that falls upon the wavelength shifter in addition to the Cherenkov light created in the bar is converted to a longer wavelength and is
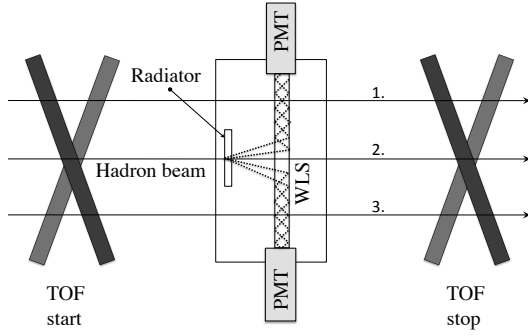
Figure 3: Schematic view of the Cherenkov detector setup along beam line. The three orientation in which the hadron bean transversed the detector are shown by the solid black lines.
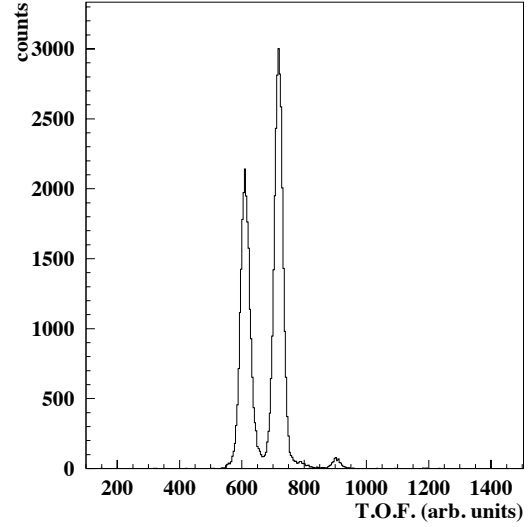

Figure 4: Time of flight distribution for pions, protons, and deuterons, left to right respectively, at 1.5 GeV/c momentum.

Table 2: Photoelectron yield of several momenta setting for protons.

$P(GeV/c)$	N.p.e(Cntr.)	N.p.e(L)	N.p.e(R)	N.p.e(Rad.)
1.05	23.9±0.2	15.0±0.2	14.0±0.1	9.3 ±0.2
1.20	32.3±0.3	18.2±0.1	20.0±0.2	13.1±0.3
1.35	38.9±0.3	21.2±0.2	23.2±0.2	16.7±0.4
1.50	43.2±0.4	25.8±0.3	24.5±0.2	18.1±0.4
1.70	46.0±0.4	28.2±0.3	29.8±0.3	17.0±0.4

isotropically re-emitted [4]. The peak of the flourescence spectrum, 400 - 450 nm, lies in the peak effective range of the photomultiplier. With an index of refraction for the wavelength shifter of n_{wls} =1.49, the critical angle for total internal reflection is 42^0. The estimated loss of light that is emitted below the critical angle is 51 percent. The quantum efficiency of the WLS is in the range of 84%, therefore, 41 percent of the light isotropically emitted should reflect along the length of the wavelength shifting bar towards the attached photomultipliers. The 12.5 cm diameter photomultipliers (PMTS) (XP457B/D1) [10] were glued to both ends of the wavelength shifter with optical cement (EJ-500) [11]. The radiator was held in position using black foam core board and the entire setup was contained within a light tight box. The implementation of the black foam core along with covering the interiors surfaces of the detector was undertaken to prevent any re-scattering of photons within the detector housing.

2.2. Method

The detector was placed along one of the secondary hadron beam line of the KEK facility. The secondary beam provides a mixed hadron beam consisting of protons, kaons, pions, and deuterons with momentum up to 2 GeV/c. Figure 3 shows the experimental detector arrangement along the beam line. The beam was extracted at several momenta; the momenta selected for the detector test were 1.05, 1.2, 1.35, 1.5 and 1.7 GeV/c. The Cherenkov opening angle is determined from the relation:

$$\cos \theta_c = \frac{1}{\beta n} \qquad (6)$$

and, thus, the opening angle for a particle whose velocity $\beta = v/c$, where β is the ratio of a particles velocity in the medium to that of light in a vacuum, equal to 1 is 52.6^0. There were two small crossed time of flight scintillators placed at the beginning and end of the beam line.The initial orientation was such that the beam was incident on the radiator as well as the WLS. This is illustrated by position 2 in Figure 3. Cherenkov light can also be produced as the the hadron beam transversed the WLS. Therefore the detector was moved to an orientation in which the beam would be directed only through the WLS and not the radiator. This was performed for both positions left and right of the radiator. Movement of the detector position allowed the calculation of the light output of the radiator from the difference between the light output gathered with beam center and that of the average of the left and right positions, where the Cherenkov light yielded was purely form the WLS. Positions 1 and 3 in Figure 3 displays these orientations.
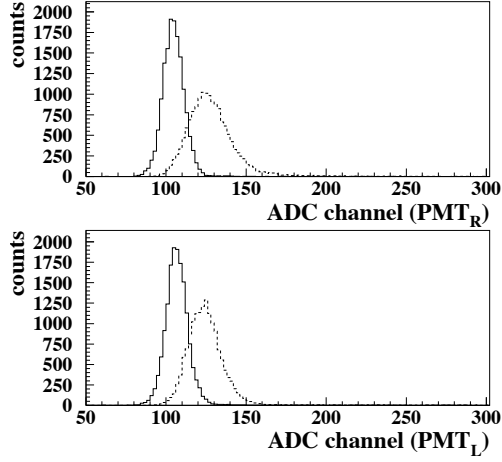
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Figure 5: Uncalibrated superposition of the pedestal and first photoelectron peak. The upper figure is the response of the right PMT, the lower is the response of the left PMT, with respect to the beam line .
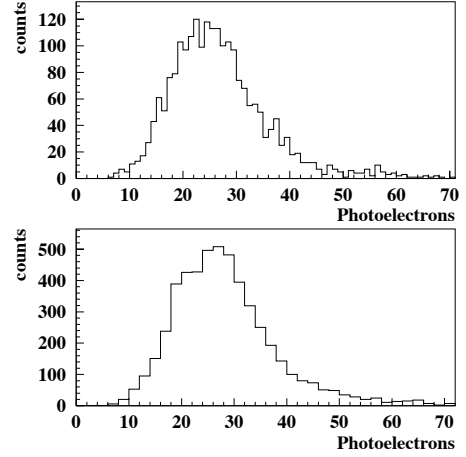

Figure 6: Calibrated photoelectron yield at 1.5 GeV/c for detector orientations. The upper figure is for the beam right position, the lower is for the beam left position. The number of photoelectrons collected at the beam right position was 24.5±0.2 and 25.8±0.3 for the left orientation.

3. Data Analysis

The time of flight distribution was a necessary part of the data analysis technique. It allowed for the proper timing cuts to be made in order to separate the light generated by each type of particle. Figure 4 shows a typical time of flight distribution. Using the determined timing conditions the appropriate cuts on the raw ADC spectra were performed. The hadron beam consisted of kaons protons and pions, however, the Cherenkov light that would be created from pions and kaons as they transversed the fused silica would be be emitted above the the critical angle for internal reflection, and would subsequently be confined within the radiator. As such, the experiment focused on the light produced from the protons. The light collected was from mainly pions and protons. The raw ADC spectra were calibrated to show the number of photoelectrons by determining the ADC pedestal channel position and ADC channel position of the one photoelectron distribution. The difference between the pedestal and the position of the one photoelectron distribution translates into a proportionality between the collected charge at the anode and the number of collected photoelectrons. An uncalibrated overlay of the pedestal and first photoelectron peak is illustrated in Figure 5. Data were obtained by triggering the data acquisition randomly and with low thresholds on the individual PMTs. The photoelectron production of the radiator at each momentum was determined by subtracting the average photoelectron yield of beam left and right, from the photoelectron yield at the beam center position. Where, at the beam center position the number of

photoelectrons detected is a combination of the amount generated by the fused silica and the wavelength shifting acrylic plastic.

4. Results

The number of Cherenkov photons detected for each momenta and detector orientation are listed in Table 2. In these results only the statistical error are reported. In Figure 8 the internally created light by the WLS and externally produced light of the radiator is shown as open triangles and solid circles respectively.The data points were fitted to a linear dependence of $N_{p.e} \cong LN_0 \sin^2\theta_c$, where the radiator index of refraction n_r is 1.476, for corresponding wavelength of $\lambda = 351$ nm and N_0 is a free parameter, a determination of the quality of the detector, and L is the thickness of the radiator. As shown, the last data point does not follow the increasing trend of the other data points, indicating that the number of photons collected was reduced due to partial internal reflection of photons within the radiator above 1.5 GeV/c or as a consequence of photon loss that may have occurred between the air and WLS boundaries. Since the final data point was not well described by the fit, a linear fit was carried out without including the last data point corresponding to a momentum of 1.7 GeV/c. The normalization of the slope to the radiator thickness of 0.8 cm , resulted in a value for $N_o = 63.86$, this would in turn, correspond to a collection efficiency of 64% for external light produced by the radiator. The number of
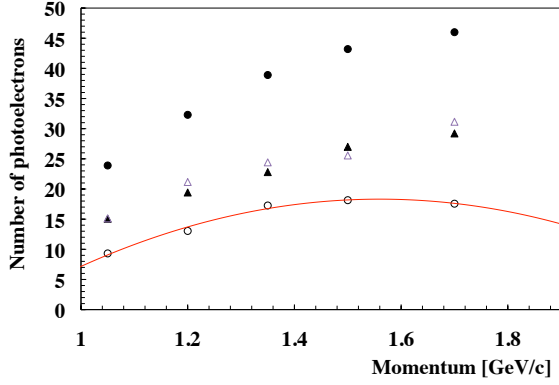
Figure 7: Number of photoelectron created by WLS and fused silica vs momentum [GeV/c]. Data points for WLS and fused silica (solid circle), WLS (triangles), and fused silica (open circle) are plotted. The redline represents fitting of data points where ϵ_{coll} and the index of refraction for the radiator n_r are both free parameters
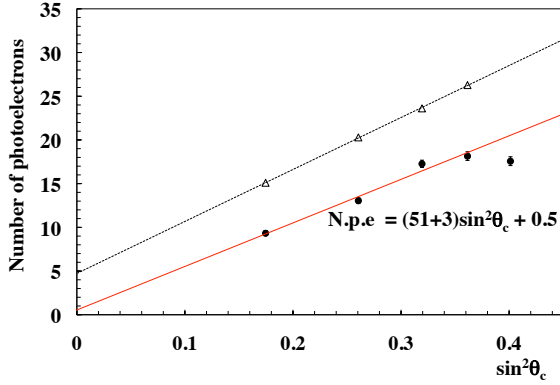

Figure 8: Number of photoelectron vs $\sin^2 \theta_c$. Data points for WLS (open triangles) response, and fused silica (solid circle) response are plotted. The lines are linear fits to the first four points.

photoelectron detected that were produced internally by the WLS itself, was calculated to be 41%.

4.1. Discussion

A wavelength-shifting Cherenkov detector was developed and a test experiment was performed at the Proton Synchrotron facility located in the National Laboratory for High Energy Physics (KEK), Tsukuba, Japan. For Cherenkov photons incident on the WLS, a collection efficiency of 64% was determined. However, if both ϵ_{coll} and the index of refraction for the radiator n_r are left as free parameters for fitting the experimental data, as shown in Figure 7 by the red line, the calculated collection efficiency is approximately 61.5%. Considering the results of both fitting procedures the collection efficiency can be concluded to be between $61 - 64\%$ for Cherenkov photons created in the fused

silica. These values are comparable to more traditional means of detecting photons in RICH detectors, like CsI photocathodes or large PMT arrays. Therefore, we are currently investigating the feasibility of using arrays of WLS bars as a means of constructing cost efficient one-dimensional RICH detectors. The design considers the use of an array of plastic bars with a wavelength shifter substance. These bars are read out by photomultipliers to map the Cherenkov cones in one dimension instead of the two-dimensional mapping of conventional RICH. The main goal is to reduce the number of PMT and the associated electronics, which in turn, reduces construction and operational costs.

References

[1] I.E. Tamm ,et al., Coherent Radiation of Fast Electrons in a Medium SSSR, 14 107 (1937)

[2] B.N. Ratcliff, Particle Physics Booklet. (2004)

[3] J.D. Jackson,Classical Electrodynamics, 3rd Edition. Wiley, New York, 1998

[4] Michael Carl, et al., Nuclear Instr. And Methods. A 527 (2004)

[5] A.Yu. Barnyakov, et al., Nuclear Instr. And Methods. A 553 (2005)

[6] J. Cohen-Tanugi, et al., Nuclear Instr. And Methods. A 515 (2003)

[7] Edmund Optics Inc.101 East Gloucester Pike, Barrington, NJ 08007-1380 USA

[8] Melles Griot Optics Guide http://www.mellesgriot.com/pdf/CatalogX/X-04-11- 13.pdf

[9] Elgen Technology,PO BOx 870, 300 Crane Street, Sweetwater,TX 79550, USA.

[10] Photonis Imaging Sensors, Avenue Roger Roncier. Z.I. Beauregard, B.P. 520 19106 Brive Cedex, France.

[11] Eljen Technology, Apace Science Inc, Mitomo-Bldg. 2-6F, 2-8, Ebisu-Nishi 2-Chome, Shibuya-Ku, Tokyo, Japan 150-0021

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